

HUNTING THE COOLEST DWARFS: METHODS AND EARLY RESULTS

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ABSTRACT

We present the methods and first results of a survey of nearby high proper motion main sequence stars to probe for cool companions with the Gemini camera at Lick Observatory. This survey uses a sample of old (age > 2 Gyr) stars as targets to probe for companions down to temperatures of 500 K. Multi-epoch observations allow us to discriminate comoving companions from background objects. So far, our survey successfully re-discovers the wide T8.5 companion to GJ 1263 and discovers a companion to the nearby M0V star GJ 660.1. The companion to GJ 660.1 (GJ 660.1B) is ~ 4 magnitudes fainter than its host star in the J-band and is located at a projected separation of ~ 120 AU. Known trigonometric parallax and 2MASS magnitudes for the GJ 660.1 system indicate a spectral type for the companion of $M9 \pm 2$.

Subject headings: stars: low-mass, brown dwarfs

1. INTRODUCTION

The unique spectroscopic properties of the lowest luminosity brown dwarfs led to the introduction of two new spectral classes, L dwarfs and T dwarfs (Kirkpatrick et al. 2005). Some wide-field searches for low temperature T dwarfs and Y dwarfs are currently in progress, and several objects with $T \sim 500$ –700 K have been discovered (Warren et al. 2007, Delorme et al. 2008, Burningham et al. 2009, Eisenhardt et al. 2010, Lucas et al. 2010, Delorme et al. 2010, Leggett et al. 2010, Mainzer et al. 2011, Burgasser et al. 2011). Although not fully characterized, the recent discovery of two cool brown dwarfs may indeed have been the first examples of the Y-type (Liu et al. 2011, Luhman et al. 2011, Rodriguez et al. 2011b). Additionally, seven ultra-cool brown dwarfs have recently been discovered with the Wide-field Infrared Survey Explorer (WISE), six of which are confirmed spectroscopically to have spectral types of Y0 or later (Cushing et al. 2011). Characterizing these Y-dwarfs will be challenging because it is very difficult to obtain reliable physical parameters such as age, distance, and metallicity, for such objects. Lowest luminosity brown dwarfs discovered as companions of stars, however, will have better constrained physical parameters since they can be inferred from the host star. For this reason, any found companion can be an important benchmark for use in the study of substellar objects. To

this end we have initiated an imaging survey to identify the coolest substellar objects as companions to nearby stars.

2. ROLE OF AGE IN SEARCH FOR Y-TYPE COMPANIONS

There will be a delay between formation of a substellar mass companion and when it has cooled to 500 K. The lower the mass, the faster 500 K can be reached. Thus, it is important to consider the masses of the lowest mass objects formed in binary systems and accessible to imaging searches. Zuckerman & Song (2009) show that the current distribution of separations and masses of imaged companions with the least mass can be accounted for by using the minimum Jeans mass fragmentation of an interstellar cloud description from Low & Lynden-Bell (1976). They show that for a fragment to split, it must have at least twice the minimum fragment mass in a typical dark molecular cloud (derived by Low & Lynden-Bell to be about 7 times the mass of Jupiter). Zuckerman & Song (2009) conclude that characteristic separations of imaged companions with the lowest masses (typically hundreds of AU with masses of 10–20 M_{Jup}) are consistent with the Jeans fragmentation model. Consequently, both observations and theory suggest that wide separation secondaries will almost always have masses $\gtrsim 10 M_{Jup}$. We assume that companions to stars will have masses $\geq 15 M_{Jup}$.

According to Baraffe et al. (2003; 2006 private communication) and Burrows et al. (2003), the time needed for a 15 Jupiter mass object to cool to 500 K is ~ 2 Gyr. The relatively small number of imaged companions with masses below $\sim 15 M_{Jup}$ implies that the detection of a

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Y-type companion with an age < 2 Gyr will be very rare. Therefore, relatively older systems will make better targets to search for cool companions. Brown dwarf secondaries having masses larger than $15 M_{Jup}$ are more common than the lowest mass companions listed in Table 1 of Zuckerman & Song (2009) (see Table 2 of same paper). These companions would have to be around stars older than 2 Gyr in order to cool to the 500 K effective temperature that might herald the onset of the Y-class. According to the models of Baraffe et al. (2003), even brown dwarfs as old as 7 Gyr would have to be less massive than $\sim 25 M_{Jup}$ to have cooled to 500 K. Therefore, Y-dwarfs themselves must be relatively low-mass.

3. SAMPLE SELECTION

We are interested in probing for Y-type dwarfs which are born with separations from their host star in the hundreds to thousands of AU range. It is for the above reasons that the targets selected for our proper motion companion search are those nearby stars with ages > 2 Gyr. Our current list of 50 targets consists of stars from the Gliese catalog because these stars tend to be old ($\gg 100$ Myr, Song et al. 2003). Stars with the highest proper motions (total proper motion ≥ 650 mas/yr) were selected from this catalog because of instrumental considerations (see Section 4). Each potential target was cross-matched with the ROSAT All-Sky Survey (RASS) with a search radius of $2'$ to check for X-ray emission as a possible indicator of age. Of the targets in our sample, seven were found to have been detected in X-rays. The X-ray luminosity measured for each still indicates an age at least as old as that of the Hyades (age ~ 600 Myr). X-ray luminosity upper limits were calculated for the remainder of our targets. Detections and upper limits for our targets are shown in Figure 1. Additionally, space motions were calculated to verify that they do not fall within the young star UVW defined by Zuckerman & Song (2004). These regions are areas of UVW space inhabited by young (age $\lesssim 100$ Myr), nearby stars. UVW space motions for our targets are plotted in Figure 2, which shows that the space motions of our targets are inconsistent with the space motions of nearby young stars. Each target was also checked for any measure of binarity to exclude those with known companions.

Our target list and current observation status are given in Table 1. Parallax measurements are from the Gliese catalog. Right ascension, declination, and J-magnitudes are from the Two Micron All Sky Survey (2MASS). Spectral type and proper motion are from the SIMBAD astronomical database. Distributions of proper motion and spectral type are shown in Figure 3. After the target list was created, we then checked each target for GALEX near ultraviolet emission as a possible additional indicator of age (Shkolnik et al. 2011, Rodriguez et al. 2011). Twenty-eight of our targets had corresponding GALEX matches. Comparison with young stars (Zuckerman & Song 2004), Hyades members (obtained from the WEBDA open cluster database), and the rest of the Gliese catalog again indicate that our sample consists of an older population (Figure 4).

4. OBSERVATIONS

Observations for this survey began in August of 2007 and we are still actively acquiring second epoch data

for selected stars. This survey is being conducted with the Gemini camera (McLean et al. 1993) located on the Shane 3m Telescope at the Lick Observatory, Mt. Hamilton, CA. The Lick Gemini camera is unique for our purposes with its combination of a wide field of view ($3' \times 3'$) and a coronagraphic spot. Our observations of main sequence F-, G-, K-, and M-type stars employ this $5''$ coronagraphic spot to best suppress scattered light and obtain maximum sensitivity in the full field of view. These observations yield a radial field of view of $\sim 90''$ and allow us to probe separations out to 900 AU at 10 pc and 1800 AU at 20 pc (distances to our targets range from 10 - 25 pc). While the smallest separations we can probe depend on the apparent brightness of the target star, the typical smallest separations to detect a source at 3σ above the background are $\sim 10''$.

Based on T dwarf spectra and theoretical models, the very low temperature objects we are seeking are anticipated to be more easily detected at J-band rather than K-band. Therefore, all targets are being observed in Gemini J-band imaging. With 30 minutes of on-source integration time per object, we can (in good conditions) achieve a limiting J-band magnitude of 20 at the 6σ detection level. Based on the Baraffe et al. (2003) models, this magnitude limit is sufficient to detect companions as old as 5 Gyr with temperatures down to 500 K out to 15 pc, and companions with temperatures down to 600 K out to 25 pc.

We search at two epochs for co-moving companions to old, high proper motion, main-sequence stars. Through the end of 2009, we have obtained first epoch images for 50 main sequence stars with spectral types from late-F to mid-M; second epoch imaging to similar depths have been obtained for 41 of these stars. All target images were reduced with custom in-house IDL software routines. Science frames were reduced by performing sky subtraction, flat division, bad pixel masking, shifting, and averaging. Source extraction for this project was done using the IRAF routine DAOFIND.

Background 2MASS sources in each field can be used to apply a world coordinate system (wcs) to each image. This is accomplished by matching pixel coordinates with 2MASS coordinates and using the IRAF task CCMAP. Once the transformation is found, a wcs can be applied to the image with the iraf task CCSETWCS. Once a wcs is applied to an image, measuring separations and position angles can be performed with the IDL routines *gcirc.pro* and *posang.pro*, both part of the IDL Astronomy User's Library. This process also allows us to calculate plate scale information for each image. We measure a GEMINI pixel scale of $0.70''$ per pixel for these observations.

4.1. Astrometry

The proper motion of a particular target can be measured and compared to any motions exhibited by stars in the surrounding field by imaging the area around the target star at two epochs separated by a sufficient interval of time. The IRAF task GEOMAP can create a general transformation between two sets of coordinates corresponding to sources in the same field at two different epochs. GEOMAP uses a polynomial fit to the sets of coordinates to account for translation, rotation, scaling, and distortion (we use the default setting of the polynomial fit, which is a power series in x and y of order

2). Residuals of the pixel shifts from one epoch to the next can be used to flag any high proper motion objects against the near zero proper motion of background stars. The scatter in the residuals of the background stars can also be used to provide a measure of our astrometric measurement uncertainty in the following manner.

Firstly, we measure the center position of background star offsets by calculating the average offset in the x and y directions using the pixel shifts from one epoch to the next. Then, from this position, we calculate the standard deviation of residuals for all background stars. This standard deviation is typically between 0.1 and 0.2 pixels for our observations. Since our targets are high proper motion stars ($\mu > 650$ mas/yr), in one year, a typical target displays a positional displacement of ~ 1 pixel with respect to background stars. Therefore, co-moving companions to our targets should be detectable at the 5-10 σ level by two epochs separated by a year.

5. EARLY RESULTS

For each observation, we calculate a 90% magnitude completeness limit. Using these limits, known parallax measurements, and the "COND" evolutionary models from Baraffe et al. (2003), we estimate the minimum mass and effective temperature of a companion that could be detected in each image. The mass and corresponding effective temperature sensitivity limits for each target that has two observed epochs of good quality are shown in Figure 5 (assuming an age of 2 Gyr). The average temperature sensitivity limit for these pairs of images is ~ 600 K. This corresponds to an average mass sensitivity limit of 0.018 solar masses (~ 19 Jupiter masses) for an estimated age of ~ 2 Gyr. One of the coolest dwarfs with a measured parallax is the T9+ dwarf UGPS 0722-05 discovered by Lucas et al. (2010). UGPS 0722-05 has an absolute J-band magnitude of 18.5 ± 0.2 . By comparing this with our magnitude completeness limits, we would be able to detect an object as faint or fainter than UGPS 0722-05 around 20 of our targets (40%).

The capability of GEOMAP to identify faint, co-moving sources with only one year time-baseline between epochs is demonstrated with our imaging of the GJ 1263 (Wolf 940; Burningham et al. 2009) wide binary system (M4 + T8.5). We first observed GJ 1263 on 2008 August 10 and again on 2009 August 28. Its co-moving companion was identified by plotting positional offsets of surrounding objects (Fig. 6) in the method described above. The 1σ uncertainty in position for background objects of median 2MASS J-mag = 16.5 is ~ 0.10 pixels. With a total offset of ~ 1.213 pixels (the total proper motion of GJ1263 is ~ 970 mas/yr), the candidate companion is $\sim 12\sigma$ away from the center of all background source residuals. Derived properties of GJ 1263B are displayed in Table 2. Absolute J magnitudes, separations, and projected separations are in good agreement with those quoted in Burningham et al. (2009).

The first new discovery of our survey is a co-moving companion to the star GJ 660.1. We observed GJ 660.1 on 2008 August 12 and again on 2009 August 30. GJ 660.1 is an M0 star located at a distance of $20.0^{+1.6}_{-1.3}$ pc (van Leeuwen 2007) with proper motion in right ascension of 189 mas/yr and -695 mas/yr in declination. GJ 660.1 was detected in 2MASS with J-band magnitude of 8.66 ± 0.03 . Radial velocity measurements (Reid et al.

1995) and the proper motions mentioned above indicate Galactic *UVW* space motions ($U = 0.5 \pm 2.1$ km s $^{-1}$, $V = -52.1 \pm 3.0$ km s $^{-1}$, $W = -60.3 \pm 3.5$ km s $^{-1}$) inconsistent with any nearby young stellar associations¹. The large negative V and large absolute value of W, along with the low position of GJ 660.1A on an HR diagram and a null Rosat All Sky Survey X-ray detection imply that the star is older than ~ 2 Gyr.

Measured residuals for the companion and background sources are shown in Fig. 6. The 1σ uncertainty in position for background objects is ~ 0.091 pixels. With a total offset of ~ 1.274 pixels, the companion to GJ 660.1 is $\sim 14\sigma$ away from the centroid of all background source offsets. Properties derived for this companion are shown in Table 2. This companion was detected by the 2-Micron All Sky Survey (2MASS) along with several background sources in our images. Residuals from this earlier 2MASS image (epoch 1999 March 31) confirm this companion at the $\sim 35\sigma$ level. Based on absolute measured and 2MASS magnitudes found for the companion and a comparison to the magnitudes of known dwarfs (using DwarfArchives.org), we estimate a spectral type of $M9 \pm 2$. Using the models of Baraffe et al. (2003), the mass of this companion is determined to be between 0.075 and 0.080 M_{\odot} for an estimated age between 1 and 5 Gyr. This companion will be discussed in a future publication in more detail.

6. CONCLUSION

We report the methods and early results of a Lick/GEMINI survey of 50 old nearby stars for cool companions. We illustrate the capabilities of our observing strategy via detection of the previously known M4 + T8.5 binary system GJ 1263AB. In addition to this rediscovery, we discovered a late M dwarf companion to GJ 660.1. By comparing position residuals versus those of stationary background objects, we conclude that GJ 660.1B is co-moving with GJ 660.1A. We also show detectable lower limits of effective temperature and mass for possible companions of our targets. Based on our detection limits, we will be able to detect companions as faint or fainter than the T9+ dwarf UGPS 0722-05 for 40% of our targets. These early results show the effectiveness of this method.

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¹ *UVW* are defined with respect to the Sun. U is positive toward the Galactic center, V is positive in the direction of Galactic rotation, and W is positive toward the north Galactic pole.

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TABLE 1
TARGET LIST

GJ #	RA (J2000.0)	DE (J2000.0)	Spectral Type	J (mag)	μ (mas yr ⁻¹)	π (mas)	Obs. Date 1	Obs. Date 2
1014	00:35:55.57	+10:28:35.21	M5	10.22	1173.08	64.0	10/10/08	...
28	00:40:49.29	+40:11:13.33	K2Ve	5.69	758.22	58.5	8/11/08	8/30/09
38	00:51:29.64	+58:18:07.14	dM2	7.83	1621.69	53.5	8/12/08	8/29/09
1025	01:00:56.44	-04:26:56.15	M3.5	9.04	1325.08	60.0	10/25/07	...
1029	01:05:37.32	+28:29:33.98	M5	9.49	1917.83	79.6	10/9/08	...
52	01:07:07.95	+63:56:28.43	K7V	6.47	1578.75	67.2	8/5/07	8/9/08
1035	01:19:52.28	+84:09:32.80	M5	9.85	1089.15	73.2	10/10/08	8/31/09
87	02:12:20.91	+03:34:31.09	dM2.5	6.83	2555.85	86.7	10/24/07	10/8/08
3181	02:46:34.86	+16:25:11.60	M6	10.97	1012.35	66.7	10/10/08	...
123	03:06:26.76	+01:57:53.84	M0V	6.49	1005.56	63.6	10/24/07	10/8/08
124	03:09:03.87	+49:36:47.94	G0V	3.14	1265.91	92.4	10/26/07	10/9/08
197	05:19:08.48	+40:05:56.59	G2IV-V	3.39	843.63	69.5	10/25/07	10/8/08
215	05:45:48.22	+62:14:13.28	K7	6.35	841.37	71.6	10/26/07	...
217	05:46:01.92	+37:17:04.38	K1V	5.83	705.57	56.7	10/10/08	...
262	07:03:30.44	+29:20:15.01	G4V	4.89	842.46	55.0	10/24/07	10/8/08
302	08:18:23.89	-12:37:54.15	G7.5V	4.95	1028.43	79.3	10/24/07	...
365	09:43:25.63	+42:41:31.00	K5V	6.09	828.46	50.5	10/26/07	10/9/08
602	15:52:40.53	+42:27:05.21	F9V	2.94	768.85	57.5	7/11/08	7/6/09
603	15:56:27.20	+15:39:41.31	F6V	3.14	1319.39	84.1	8/5/07	8/9/08
9537	16:01:02.65	+33:18:12.48	G0V	4.09	758.98	60.0	7/8/08	7/3/09
609	16:02:50.98	+20:35:21.83	M3	8.13	1551.35	99.4	8/10/08	8/29/09
651	17:02:36.40	+47:04:54.03	G8V	5.41	864.43	61.8	7/9/08	7/4/09
1209	17:04:22.34	+16:55:55.22	M2.5	8.57	1135.29	57.9	7/11/08	7/6/09
660.1	17:12:51.27	-05:07:31.17	M0	8.66	720.31	49.6	8/12/08	8/30/09
672	17:20:39.55	+32:28:05.69	G2V	4.16	1048.72	73.7	8/6/07	8/9/08
700.2	18:02:30.85	+26:18:47.10	K0V	5.55	717.41	53.0	8/11/08	8/30/09
1225	18:17:15.09	+68:33:19.92	M4.5	10.78	1730.67	54.3	7/9/08	7/4/09
712	18:22:06.71	+06:20:37.70	M3	8.67	1139.96	69.1	8/12/08	8/31/09
740	18:58:00.14	+05:54:29.70	M2V	6.23	1234.96	94.6	7/10/08	7/5/09
1235	19:21:38.68	+20:52:02.82	M4.5	8.79	1731.88	98.4	7/8/08	7/3/09
759	19:24:58.23	+11:56:40.15	G8IV	3.55	965.93	64.3	7/9/08	7/4/09
1248	20:03:50.99	+05:59:44.02	M1.5	8.63	935.45	78.9	7/11/08	7/6/09
778	20:03:52.10	+23:20:26.27	K1V	5.67	1356.05	55.0	7/8/08	7/3/09
1254	20:33:40.31	+61:45:13.57	M4	8.29	1061.60	62.5	8/10/08	8/31/09
9711	20:56:46.59	-10:26:53.43	dM4	7.76	1109.96	56.3	8/10/08	8/29/09
817	21:04:53.42	-16:57:31.11	M2	8.28	2233.71	57.5	10/26/07	10/8/08
9722	21:07:55.43	+59:43:19.89	sdM1	10.12	2109.90	41.7	8/11/08	8/30/09
821	21:09:17.41	-13:18:08.03	M3	7.68	2117.76	91.7	7/10/08	7/5/09
830	21:30:02.72	-12:30:36.15	M0V	6.65	1052.66	63.6	8/6/07	8/9/08
1263	21:46:40.40	-00:10:23.35	M3.5	8.36	969.92	81.8	8/10/08	8/29/09
4239	21:56:55.14	-01:54:10.05	dM5	9.88	1408.69	75.0	10/9/08	...
1266	22:16:20.29	+70:56:39.53	M2	8.74	863.38	44.5	10/26/07	10/8/08
1271	22:42:38.72	+17:40:09.11	M3	8.06	1220.71	52.6	8/11/08	8/30/09
4312	23:07:30.04	+68:40:05.13	M3.5	8.62	1145.09	63.5	10/26/07	10/9/08
4333	23:21:37.52	+17:17:28.47	M4	7.39	1485.52	92.8	7/9/08	7/5/09
4336	23:26:32.39	+12:09:32.83	M3	8.96	747.90	47.0	8/12/08	8/31/09
895.4	23:31:22.20	+59:09:55.86	K0V	5.34	1113.05	56.1	10/25/07	10/9/08
4346	23:35:44.45	+41:58:03.81	M0	8.10	717.47	44.0	8/11/08	8/30/09
1292	23:57:44.10	+23:18:16.97	M3.5	7.8	1465.89	72.1	8/9/08	8/29/09
4385	23:59:49.41	+47:45:44.80	M5	10.86	893.44	59.8	10/10/08	...

TABLE 2
COMPANION PROPERTIES

Observed Quantity	GJ 1263 B	GJ 660.1 B	Epoch ^a
2MASS J-Mag		13.05 ± 0.05	
2MASS H-Mag		12.57 ± 0.02	
2MASS K-Mag		12.23 ± 0.03	
Absolute 2MASS J-Mag ^b		11.6 ± 0.5	
Absolute 2MASS H-Mag ^b		11.1 ± 0.5	
Absolute 2MASS K-Mag ^b		10.7 ± 0.5	
Gemini J-Mag	18.42 ± 0.25	13.16 ± 0.21	1
Absolute Gemini J-Mag ^b	17.9 ± 0.7	11.7 ± 0.5	1
Separation (")	31.55 ± 0.01	6.00 ± 0.02	1
Projected Separation (AU) ^b	395 ± 22	120 ± 9	1
Position Angle (°)	250.4 ± 0.1	353.1 ± 0.1	1
Gemini J-Mag	18.29 ± 0.27	12.99 ± 0.21	2
Absolute Gemini J-Mag ^b	17.8 ± 0.7	11.5 ± 0.5	2
Separation (")	31.64 ± 0.01	6.08 ± 0.02	2
Projected Separation (AU) ^b	396 ± 22	121 ± 9	2
Position Angle (°)	250.5 ± 0.1	353.2 ± 0.1	2

^a See text for epochs.

^b Values and uncertainties account for distance and uncertainty in distance to each object ($12.50^{+0.75}_{-0.67}$ pc for GJ 1263B and $20.0^{+1.6}_{-1.3}$ pc for GJ 660.1B).

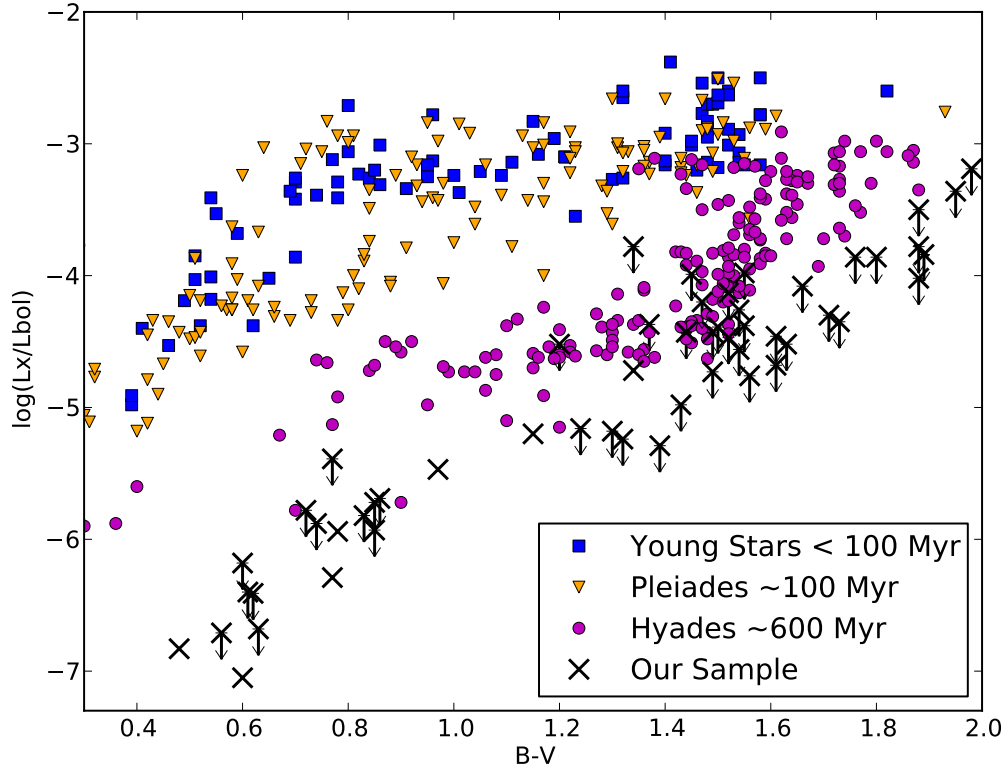


FIG. 1.— X-ray detections and upper limits for targets in our sample with RASS detections. Crosses indicate detected sources, while downward arrows indicate upper limits. Young stars, Pleiades, and Hyades data points are from Zuckerman & Song (2004).

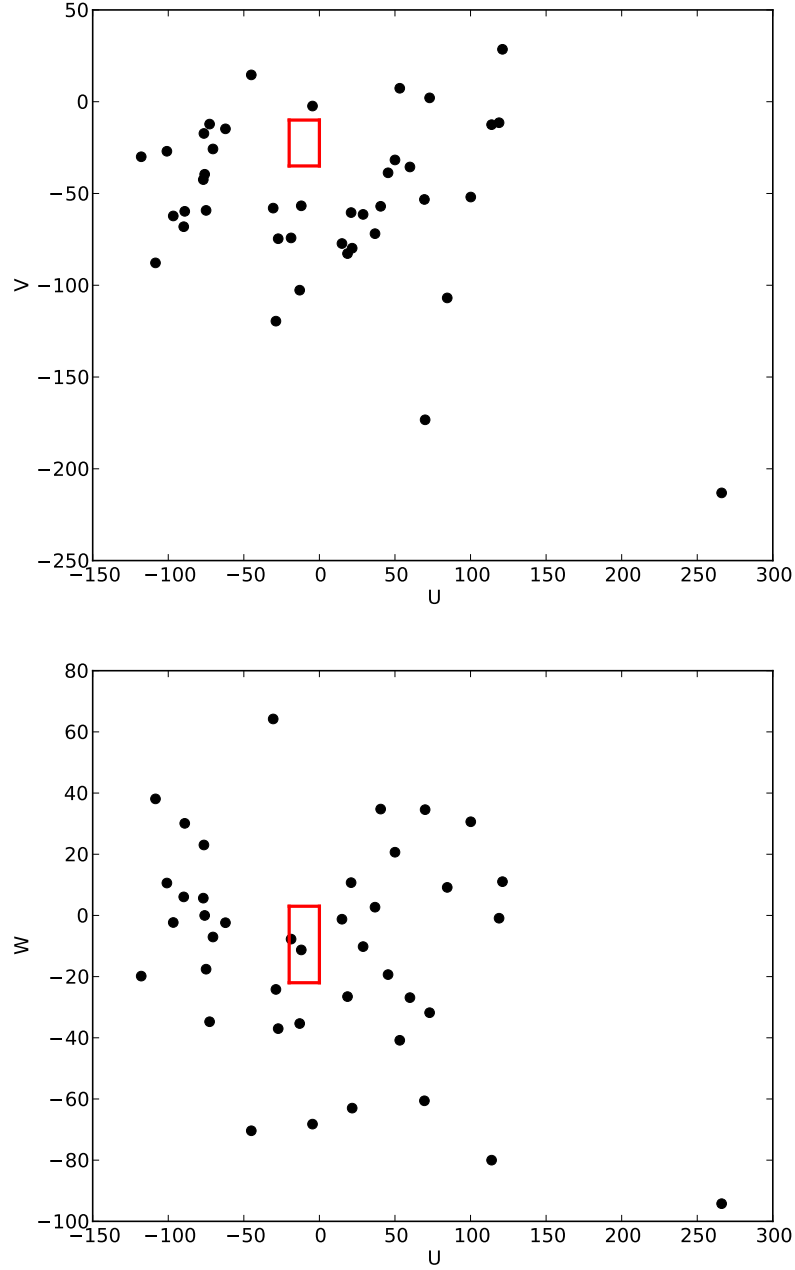


FIG. 2.— UVW space motions for our selected targets. The red box is the "good box" mentioned in the text. For a target to be consistent with young nearby star space motion, it would need to occupy space in the "good box" region in both plots. None of our selected targets do so.

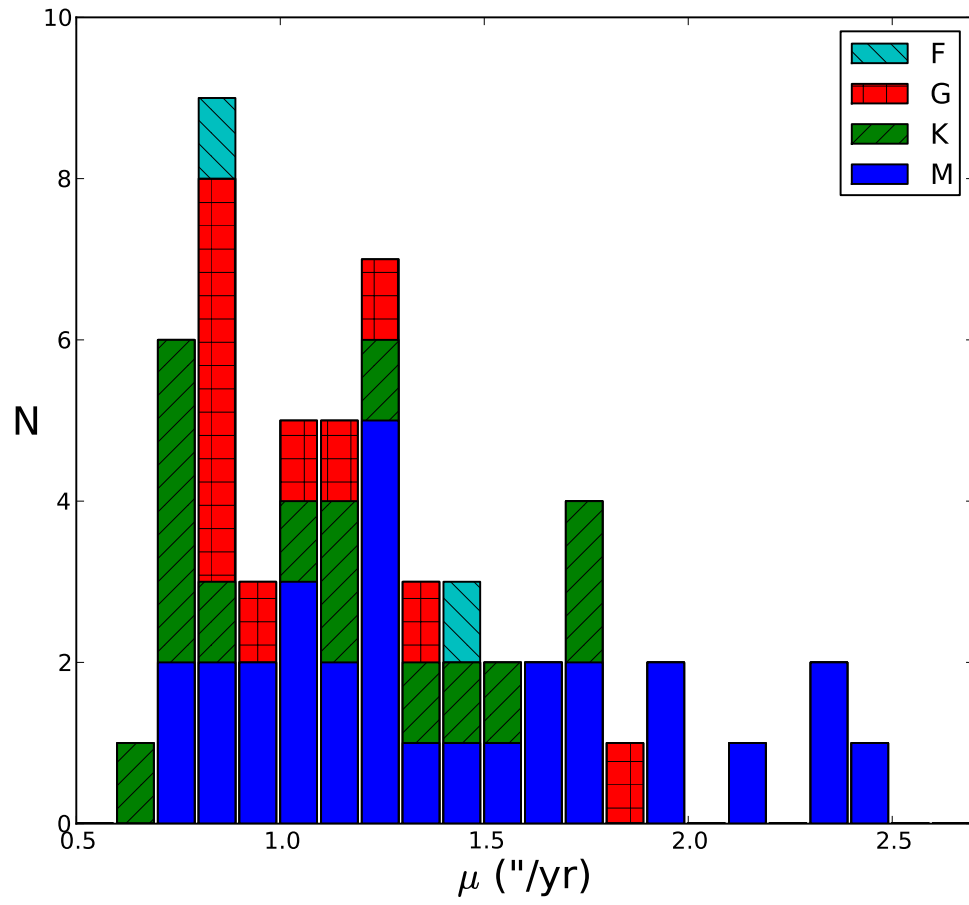


FIG. 3.— Histogram of total proper motion (μ) for the target sample. Colors indicate spectral type.

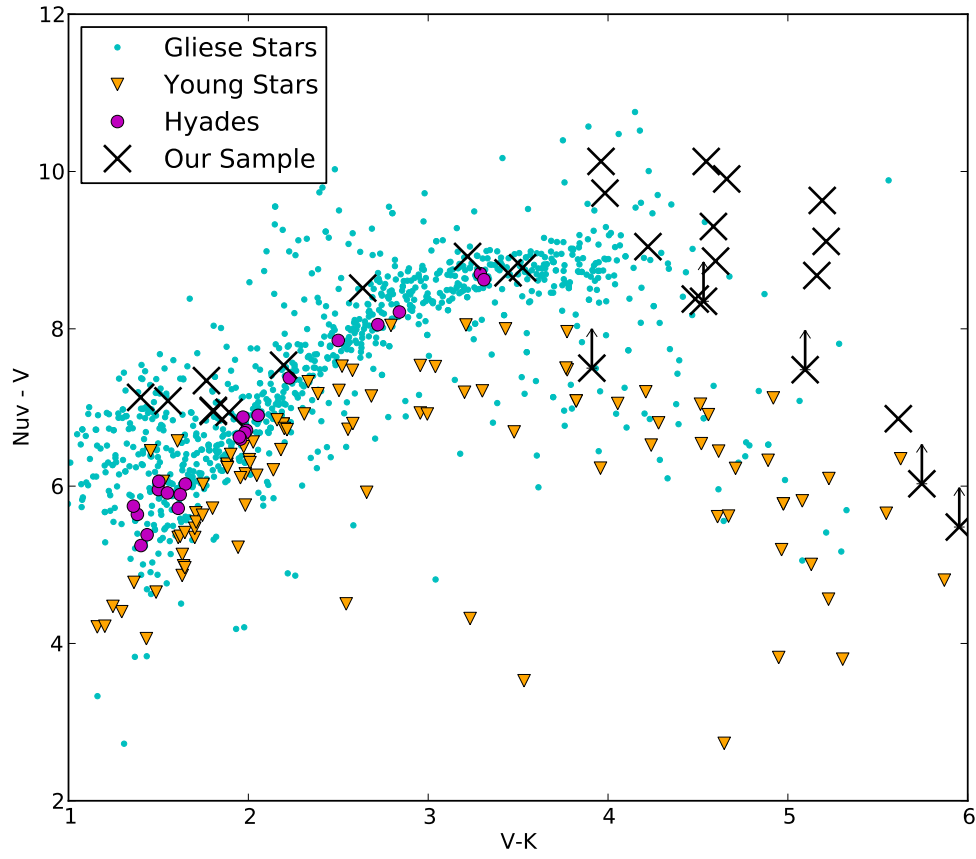


FIG. 4.— Gallex detected targets in our sample. Upward pointing arrows indicate limits on stars without Gallex counterparts within the Gallex coverage area. Young stars are from Zuckerman & Song (2004). Hyades members were obtained from the WEBDA open cluster database.

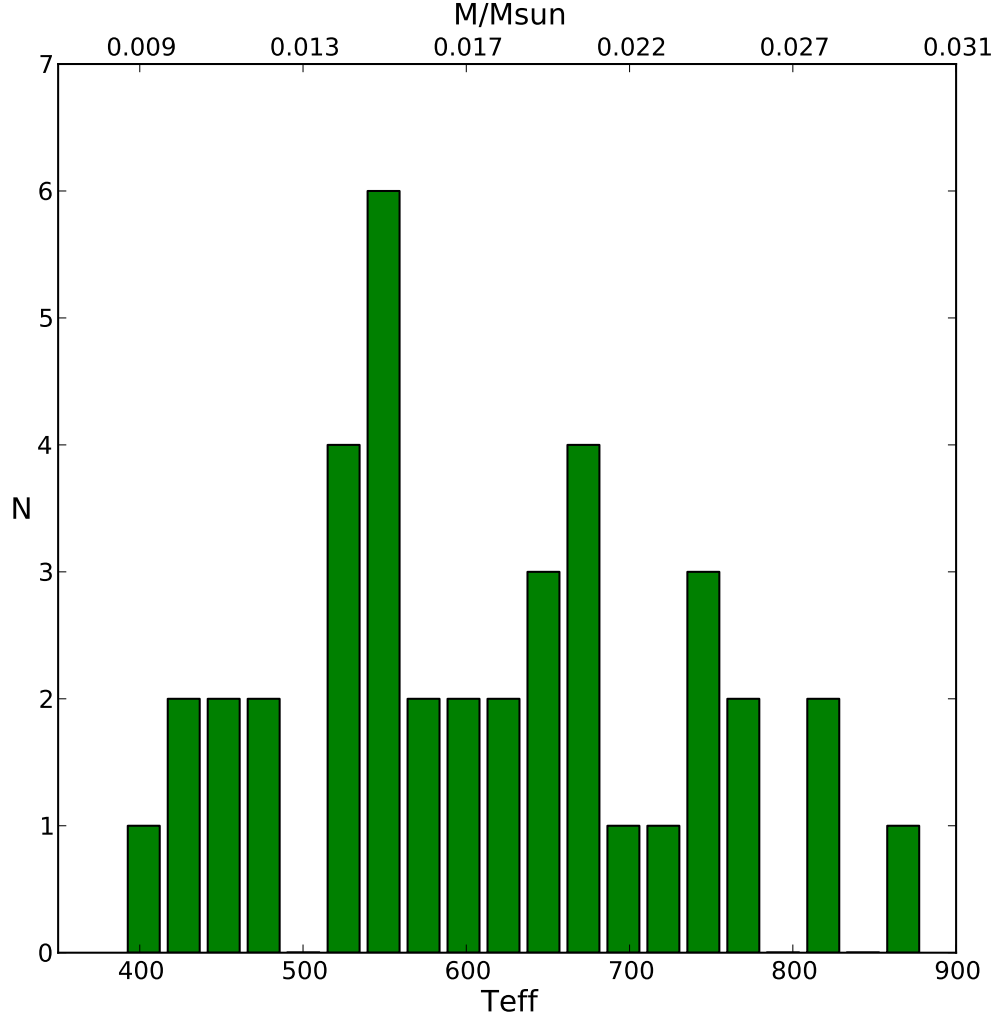


FIG. 5.— Histogram of effective temperature lower limits for each pair of observations. Corresponding lower mass limits are shown on the upper axis. Determination of these values is discussed in section 5.

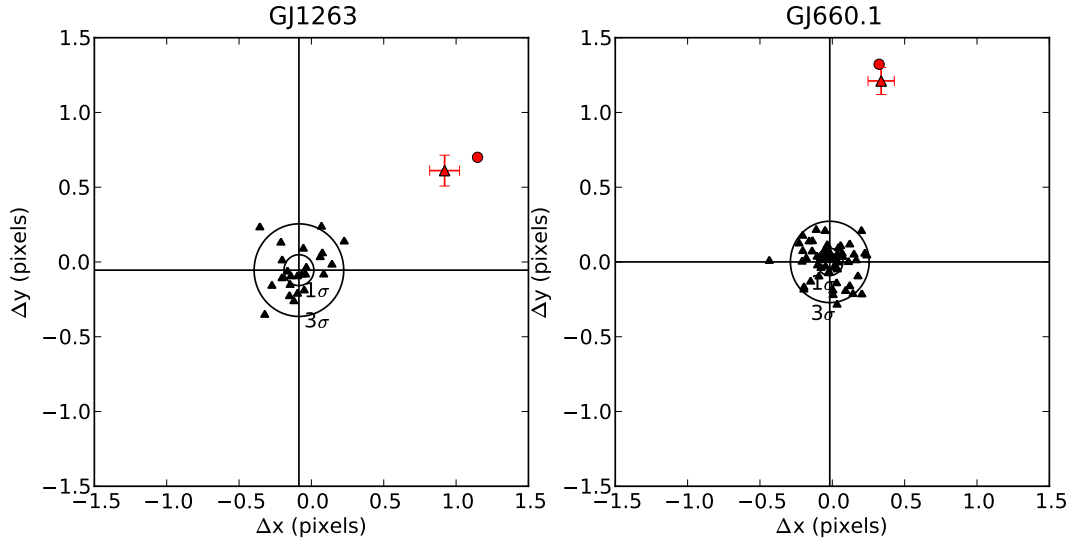


FIG. 6.— *Left:* Residuals from alignment of background reference stars (black triangles) with GJ1263A (red circle) and GJ1263B (red triangle) between two epochs. *Right:* Residuals from alignment of background reference stars (black triangles) with GJ660.1A (red circle) and GJ660.1B (red triangle) between two epochs. Positions of primaries are calculated from recorded catalog positions and known parallax and proper motions.